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AUTHOR Selleck, Ben: Espy, John
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ABSTRACT

This fourth in a series of eight modules for a course titled Metrology describes the universal bevel protractor and the sine bar, the engineering microscope and optical projector, and several types of surface texture gages. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10) test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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COURSE 27 METROLOGY

MODULE 27-4 Angle Measurement Instruments, Optical Projectors and Surface Texture Gages

CE 024 250

GENERAL PHYSICS CORPORATION
Columbia, Maryland

COURSE MODULES

COURSE 27 METROLOGY

Module 27-1	Fundamentals of Metrology
Module 27-2	Fixed Gages, Dividers, Calipers and Micrometers
Module 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
Module 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
Module 27-5	Tolerancing
Module 27-6	Calibration
Module 27-7	Statistical Techniques in Metrology
Module 27-8	The Total Measurement System

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This module was prepared for General Physics Corporation by John Espy, General Physics Corporation, and Ben Selleck, Ben-Sel Associates.

GENERAL PHYSICS CORPORATION

1979

INTRODUCTION

A QA/QC Technician often works with devices which measure angles as well as devices which measure surface texture or smoothness. Many critical dimensions are angular measurements. The surface texture of parts such as bearings and seals are critical to their performance. The QA/QC technicians must not only understand how these dimensions are measured but he must understand the limitations of the measurement devices and the sources of error when they are used.

This module describes the most common devices used to measure angles and surface texture. Specifically, it describes the universal bevel protractor and the sine bar, which are used to measure angles, the engineering microscope and optical projector, which are also used to measure angles but which have several additional uses, and several types of surface texture gages.

MODULE PREREQUISITES

The student/trainee must be familiar with the terms and units of angular measurement. Introductory course work in geometry and trigonometry are useful for this module. The student/trainee also shall have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Describe the following instruments and their general operation: (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
2. Demonstrate measurement of acute and obtuse angles with (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
3. Name at least three sources of error in measurements with (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
4. Demonstrate measurement of distance and form with an optical projector.
5. Define the following surface texture terms: (a) roughness, (b) roughness height, (c) roughness width cutoff, (d) waviness, (e) waviness height and (f) lay.
6. Match surface texture symbols with their application and recognize and interpret data associated with these symbols as given on engineering drawings.
7. Demonstrate measurement of roughness and waviness height.

NOTES TO INSTRUCTOR / STUDENT

The objectives of this module require the student/trainee to demonstrate knowledge of specific instruments and

skill in using them. The activities provided involve use of these instruments; however, parts to be measured and the specific instrument to be used must be selected in advance. Parts selected should possess (1) acute and obtuse angles, (2) inside and outside lengths, (3) surfaces with toleranced surface texture and (4) for the optical projector, geometric forms of parallelism and perpendicularity. Screw threads are suggested for use with the optical projector.

Because this module makes reference to basic geometric and trigonometric concepts. It would be useful for the instructor to review the basic concepts of angular measure, types of angles, Pythagorean Theorem and the sine, cosine and tangent functions employed in trigonometry.

ANGLE MEASUREMENT

Units

Most hardware industries in the United States use the sexagesimal system for designating angular relationships of mechanical features. The basic unit is the degree (°), where a full circle has 360° and a right angle, 90°. Each degree is divided into 60 seconds (') (1° = 60') and each second is divided into 60 minutes (") (1' = 60"). When angles are measured in radians, a full circle has 2π radians and a right angle has $\frac{\pi}{2}$ radians. The relationship between degrees and radians is 1 radian = 57.296° and $1° = \frac{\pi}{180}$ radians.

Types of Angle Measurement Devices

Devices used to measure angular relationships generally fall into the categories of (1) fixed gages, (2) protractors, (3) indexing tables and (4) optical devices. Fixed gages, such as taper plugs and ring gages are used to measure angles. Angular gage blocks can be used to measure angles up to 90°. Protractors range from simple semicircles with degree marks to more elaborate devices such as the universal bevel protractor. A wide variety of indexing tables are used in machining angular features. They can also be used for measuring angular relationships, either integral with machines or as separate devices. Indexing tables are available with one, two or three indexing coordinates. Optical devices used to measure angles include the engineering microscope and the optical projector.

UNIVERSAL BEVEL PROTRACTOR

Description

The universal bevel protractor, shown in Figure 27-4-1, employs precision straight edges in direct contact with the physical boundaries of the angle being measured. The sliding blade is fixed to a reference point of the primary circular scale such that its straight edge forms a tangent to the reference point. It can be slid along its longitudinal axis to offer various lengths of tangential straight edge. The non-sliding blade rotates about the center of the primary scale. The vernier scale is fixed to the hub of the rotating blade and provides the point of readout. The auxiliary blade assists in the measurement of acute angles. In most designs, the detachable auxiliary blade can be positioned parallel to or at right angles to the rotatable blade. Figure 27-4-2 illustrates typical measurements using a universal bevel protractor.

Reading the Scale

The 360° scale of the universal bevel protractor is graduated in one degree increments and divided into four 90° quadrants. From the reference point of the sliding straight edge, the scale progresses in either direction from 0 to 90° and back to 0° at the point 180° from the initial zero. The vernier scale is graduated in five minute increments with twelve increments to each side of zero. The zero on the vernier scale is the starting point for determining the readout. The increments on the vernier provide discrimination of 5'.

The basic principles of reading the scale of a universal bevel protractor is illustrated by the simplified sketch in Figure 27-4-3. The sketch shows a line tangential to the reference 0° point of the primary scale. When the

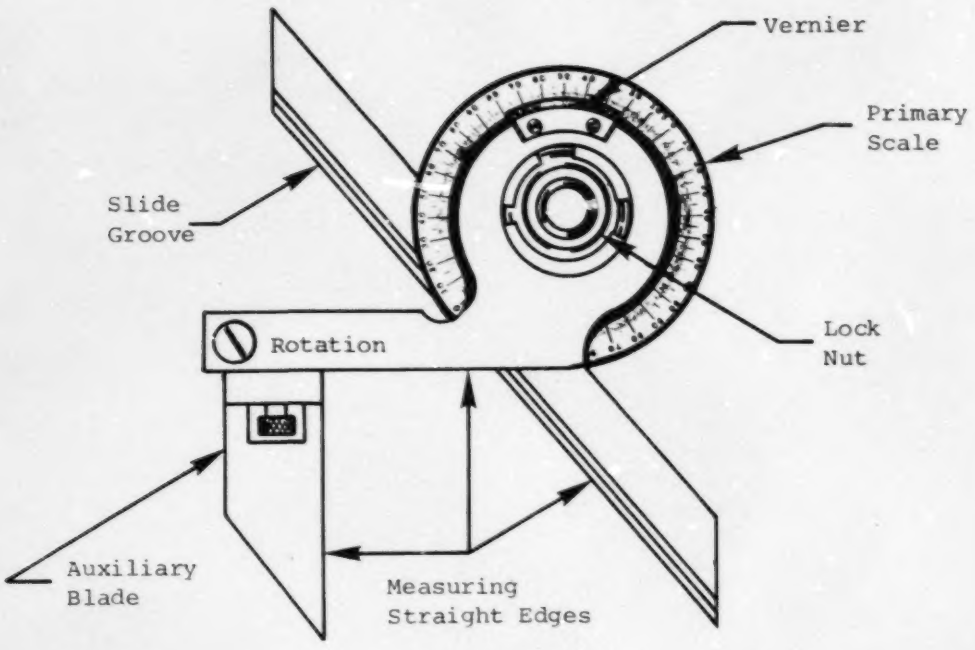


Figure 27-4-1 Universal Bevel Protractor

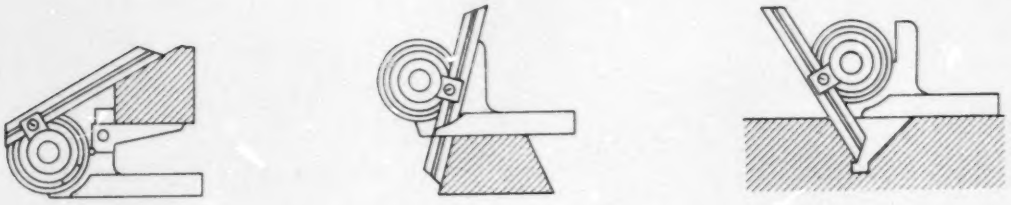


Figure 27-4-2 Measurements Using Universal Bevel Protractor

rotatable line forms a right angle with the tangential line, the hub arrow is scribed to read 90°. The arrow represents the zero of the vernier scale of an actual bevel protractor. As the rotatable line is rotated, the fixed arrow will read either the angle measured or the supplement of the angle measured.

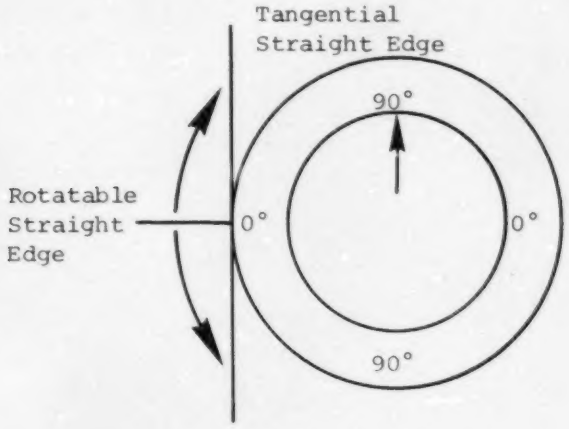
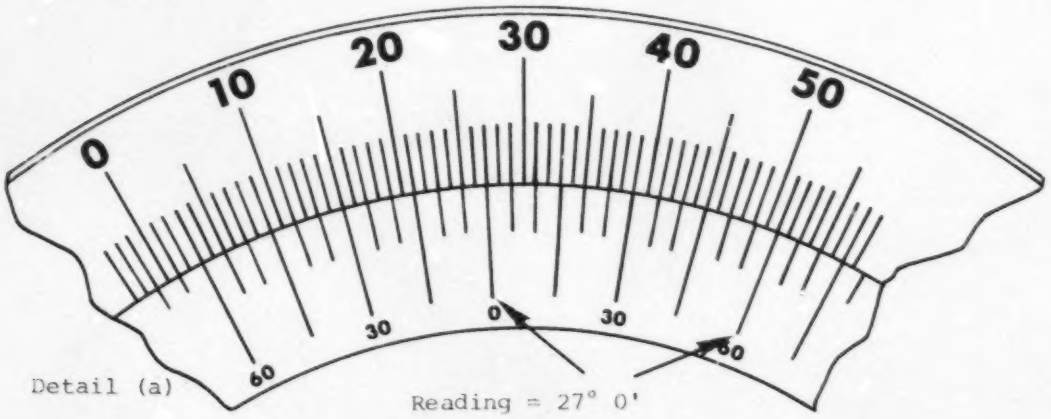


Figure 27-4-3 Reading the Scale of a Universal Bevel Protractor

Figure 27-4-4 shows how readings are obtained. The zero of the vernier identifies the whole degrees as read from the primary scale at the vernier zero. Minutes are read on the vernier in the same direction from zero as the vernier moved from zero of the primary scale. In the first example shown in Figure 27-4-4, the vernier zero indicates 27 degrees. Visual inspection of the vernier scale to the right (same direction as from zero of the primary scale) identifies that the coincident line of the vernier with the primary scale is 60 minutes. Therefore, the reading is exactly 27 degrees, or, 27° 0'. In the second example shown in Figure 27-4-4, the vernier zero indicates 27 degrees. In this case, the lefthand vernier scale coincides with the primary scale 15'. Therefore, the

reading is 27 15'. In actual measurements, one must be observant of whether the direct reading is the measured angle or its supplement. For supplements, the reading is subtracted from 180°.



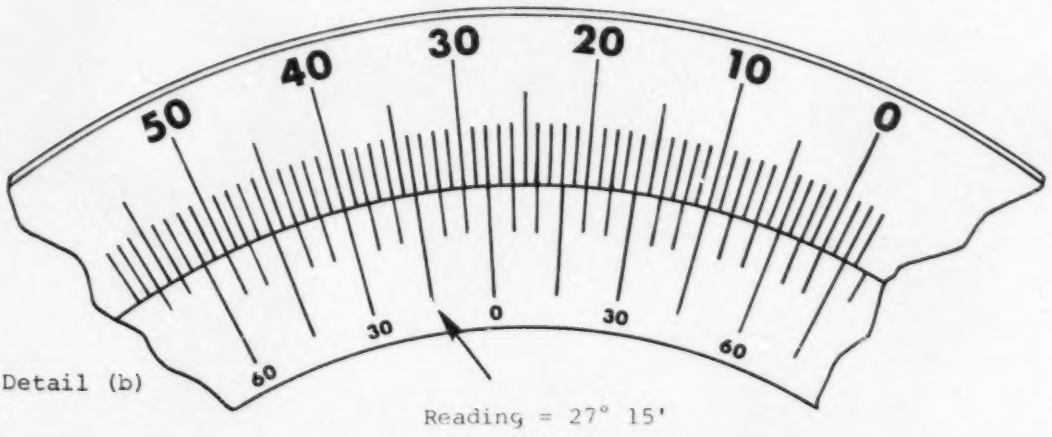


Figure 27-4-4(a) and (b) Reading the Vernier of a Universal Bevel Protractor

Accuracy and Error Sources

The accuracy of measurements with a universal bevel protractor depends on the inherent accuracy of the instrument which is best determined by calibration. Inherent features affecting accuracy are the straightness of the edges of the blades, the bearing accuracy of the rotatable blade, and the scale accuracy.

With respect to procedural errors using a universal bevel protractor, the most common are manipulative errors, readout errors, and lack of cleanliness of bearing surfaces. Manipulative errors result in a misalignment of blade straight edges with the boundaries of the angle. Readout errors stem from incorrect reading of the vernier and incorrect calculations. Foreign materials or burrs on the surfaces of the angle boundaries cause a misalignment of straight edges with such boundaries. Figure 27-4-5 illustrates misalignments that are caused by either manipulative errors, foreign materials, or burrs.

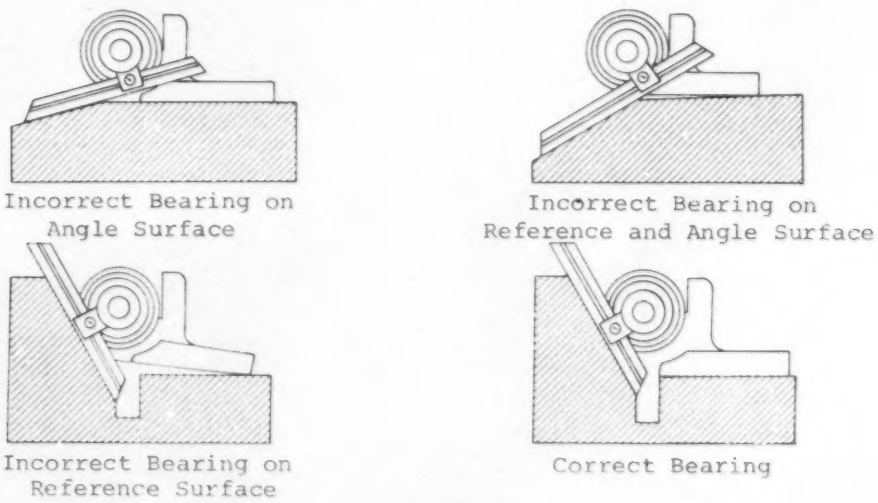

Incorrect Bearing on Angle Surface
Incorrect Bearing on Reference and Angle Surface
Incorrect Bearing on Reference Surface
Correct Bearing

Figure 27-4-5 Alignment of Universal Bearing Protractor Straight Edges

SINE BAR

Description

The sine bar is a hardened, stabilized, precision ground and lapped tool for accurate angle measurement. It consists of a flat bar to which two cylinders of equal diameter are attached at a known separation. When the cylinders are brought in contact with a flat surface, the top of the bar is parallel to that surface. Starting from this position, if a block of known height is placed under one of the cylinders, the angle by which the top surface of the bar becomes tilted can be calculated. The flat working surface can also be a block or plate. Hence, this class of tool includes sine bar, sine block, and sine plate. Figure 27-4-6 shows a sine bar with its case.

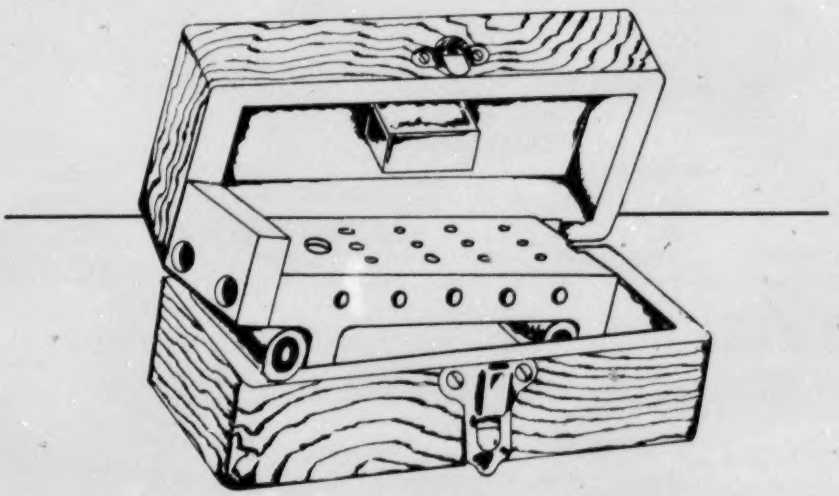


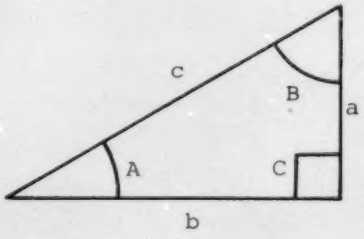
Figure 27-4-6 Sine Bar with Case

Sine bars are suitable for measuring angular features of relatively small parts when either tolerance or access limitations make the universal bevel protractor unsuitable. In general, a sine bar is more suitable than a universal

bevel protractor when angles are toleranced in minutes.

Principles of Use

Sine bars measure angles by using basic trigonometric functions of a right triangle. These basic functions are shown in Figure 27-4-7. If two sides or one side and one angle of a right triangle are known, the remaining variables can be determined. Table 27-4-1 shows the calculations required.



a = Altitude
b = Base
c = Hypotenuse

$\angle A = 90° - \angle B$
$\angle B = 90° - \angle A$
$\angle C = 90°$

$$a^2 + b^2 = c^2$$

$\sin A = \frac{a}{c}$ $\quad$ $\sin B = \frac{b}{c}$

$\cos A = \frac{b}{c}$ $\quad$ $\cos B = \frac{a}{c}$

$\tan A = \frac{a}{b}$ $\quad$ $\tan B = \frac{b}{a}$

Figure 27-4-7 Basic Trigonometric Functions

Table 27-4-1 Basic Trigonometric Calculations

Known	Calculation
Two Sides	Determine the third side using $a^2+b^2=c^2$; determine the angles using trigonometric functions.
One Side and One Angle	Determine the other angle by subtraction; determine the second side using a trigonometric function; determine the third side using $a^2+b^2=c^2$.

A sine bar consists of two equal-sized, hardened, and precision ground cylinders attached to a straight, rectangular bar. The axes of the cylinders are parallel to the working surface of the bar, and the center distance between the two cylinders is a fixed dimension. The sine bar serves as a constant hypotenuse of a length equal to the center-to-center distance of the two cylinders. This known length is 5, 10, or 20 inches dependent on the particular size of the sine bar.

As shown in Figure 27-4-8, the sine bar serves as a reference plane at a known angle. The angle at which the sine bar is placed is calculated using Equation 27-4-1. When inspecting parts, the angle and its tolerance are specified by drawings of the part. With the nominal angle thus known, the gage block height required to set the sine bar is calculated using Equation 27-4-2.

$$\sin \theta = \frac{h}{c} \qquad \text{(Eq. 27-4-1)}$$

$$h = c \sin \theta \qquad \text{(Eq. 27-4-2)}$$

Where

θ = sine bar angle

h = height of gage blocks

c = standard length of the sine bar

In determining the gage block height, attention must be given to the reference plane established on the sine bar in relation to the part feature. Figure 27-4-9 shows three methods for mounting a part on a sine bar and how these methods affect the angle being measured.

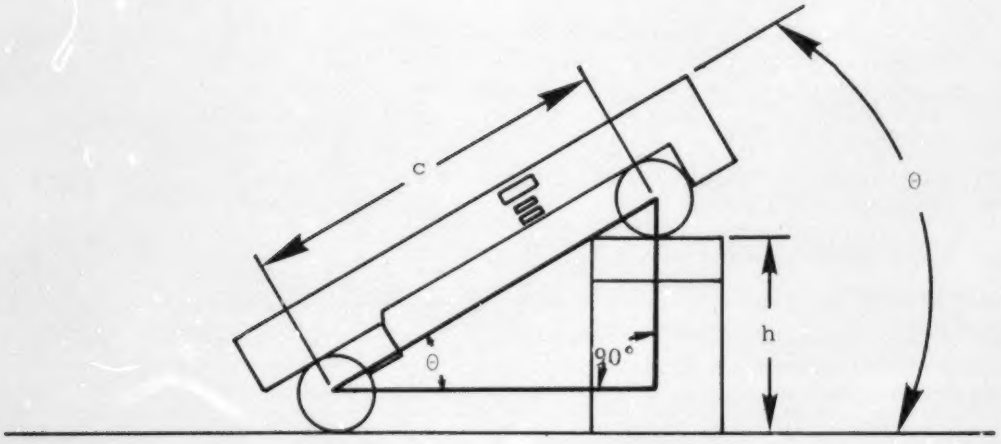


Figure 27-4-8 Sine Bar Relationships

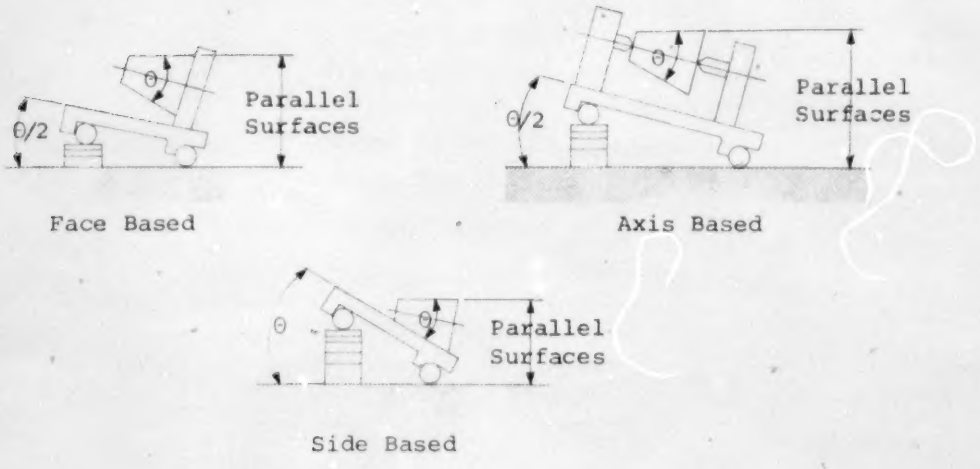


Figure 27-4-9 Sine Bar Mounting Methods

With a part mounted by one of the methods shown in Figure 27-4-9, a height indicator is used to measure the height variation along the angle surface that is nominally parallel to the reference plane. Any height variation indicates angular deviation from the nominal angle. The height to angle deviation relationship is calculated using Equation 27-4-3.

$$\tan \phi = \frac{i}{\ell} \qquad \text{(Eq. 27-4-3)}$$

Where

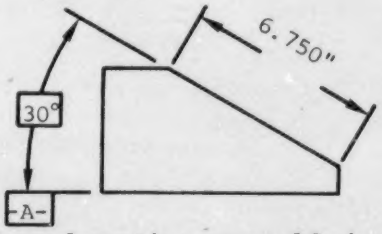
ϕ = angular deviation

i = indicated height variation

ℓ = length of surface explored to obtain the height variation

EXAMPLE

Problem: Using a ten inch sine bar, show the calculations associated with measuring the angle of the following part.



Given: Sine bar length = c = 10 in.

Part angle = θ = 30°

Height variation = i = 0.015 in.

Length of exploration = ℓ = 6.750 in.

Solution: Determine gage block stack height.

$h = c \sin \theta$

$h = (10 \text{ in.})(\sin 30°)$

$h = (10 \text{ in.})(0.5)$

$h = 5 \text{ in.}$

Mount datum A on measuring surface of sine bar; place 5 inch gage block (or a 4" and 1" wrung into a stack) on surface plate and under one cylinder of the sine bar.

Using a test indicator height set, explore the surface of the angular feature to determine height variation.

Calculate the angular deviation:

$$\tan \theta = \frac{i}{\ell}$$

$$\tan \theta = \frac{0.015 \text{ in.}}{6.750 \text{ in.}}$$

$$\tan \theta = 0.0022$$

$$\theta = 0.127° (0°7.64') (0°7'38")$$

If the angle were bilaterally toleranced (e.g., $\pm$ x°), an acceptance decision is made without regard to the direction of the angular deviation. However, if limit or unilateral tolerancing applies (e.g., 30° maximum or $30° \pm \frac{0}{x°}$) the direction of angular deviation must be determined. If the angular surface is explored from the vertex end, a negative height deviation indicates a decreasing angle while a positive height deviation indicates an increasing angle.

Accuracy and Error Sources

Sine bars are provided with inherent accuracy of about 10 seconds of arc for commercial grades and about 5 seconds of arc for laboratory grades. Sine bar features which determine the inherent accuracy are flatness and squareness of the working surface, roundness and straightness of cylinders, parallelism of cylinders with each other and the working surface, and accuracy of the center distance between cylinders.

Accuracy of sine bar measurements is less than the inherent accuracy of the sine bar. Error sources include misalignment in the mounting of parts which introduces cosine errors, precision of measuring the gaging distance of the surface explored by the height gage, errors of the

height gage, flatness of the surface plate, and calculation errors.

ENGINEERING MICROSCOPES

Description

Engineering microscopes are optically assisted instruments for measuring lengths, angles and geometric forms. The microscope permits observation of part features coincident with the optical axis of the instrument. Measurement of features is obtained by measuring the displacement of the part necessary for optical alignment with the boundaries of the feature being measured. Such measurement is by micrometer lead screws or with graduated scales within the field of view or a combination of these.

Most engineering microscopes employ collimated light passing by the object being measured to the microscope. In this manner a silhouette of the object is viewed. For observation of recesses where silhouetting is impossible, the reflection of light from the object permits measurement. The basic parts of a common silhouetting engineering microscope are shown in Figure 27-4-10.

A typical measuring instrument employing an engineering microscope is shown in Figure 27-4-11. The precision table of this instrument serves as a reference plane. It is adjustable in two coordinates by micrometer lead screws. An optical protractor located within the gratical chamber permits measurement of angles. Both silhouetting and reflecting light sources are included.

The universal measuring microscope shown in Figure 27-4-11 has eyepieces and objective lenses which provide the amount of magnification required. The graticle has precisely aligned cross hairs, and the

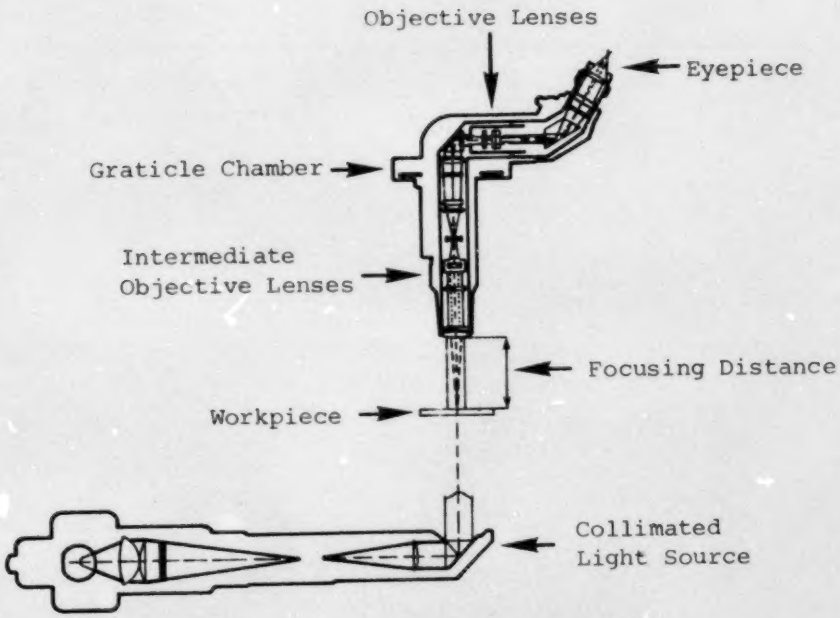


Figure 27-4-10 Engineering Microscope

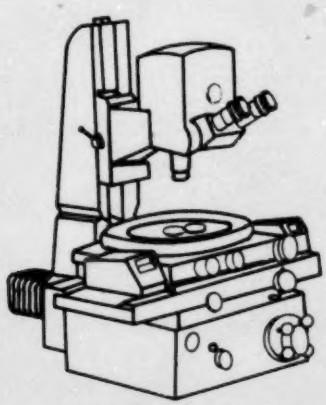


Figure 27-4-11 Universal Measuring Microscope

protractor rotates the graticle to position the cross hairs for angular measurement. The two micrometer heads permit 1" movement of the stage in either direction and are graduated for readings to 0.0001". A typical view of optical protractors is given in Figure 27-4-12. The master scale of 360° is superimposed on a readout scale graduated in minutes. One boundary of the silhouette is aligned with a

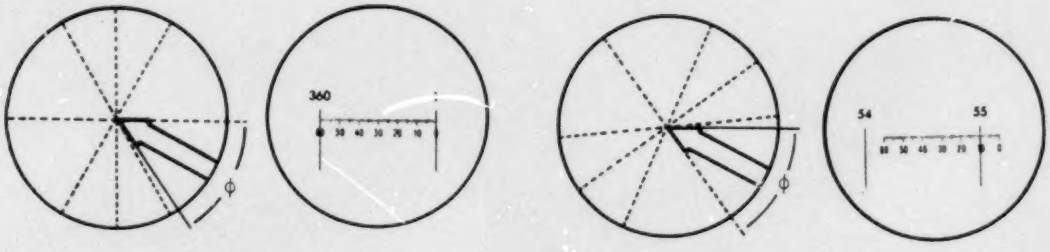


Figure 27-4-12 Angle Measurement with an Optical Protractor

cross hair at a reading of 0°. The other boundary is aligned with a cross hair showing a reading of 54°10'. The difference between these two readings is the angle formed by the object being measured. The initial setting is of no consequence since the difference between the two readings equals the measurement.

Engineering microscopes can also be used to make linear measurements. The workpiece is placed on the stage and aligned with the cross hairs. Using the micrometer heads, the reference point on the work is brought under the cross hair and a reading taken. The work is then moved with the micrometer to bring the point being measured under the same cross hair. A second reading is taken, and the difference is the measurement.

Accuracy and Error Sources

Accuracy of angular measurements with the optical protractor can be as much as plus or minus 30 seconds. For those containing a vernier, accuracy can be as much as plus or minus 10 seconds. Aside from the excellent accuracy and precision of the instrument itself, procedural errors typically include part misalignment, reading errors and calculation errors.

OPTICAL PROJECTORS

Description

Optical projectors are optically assisted instruments for measuring lengths, angles and geometric forms by projection of an image of the object being measured on a screen. Figure 27-4-13 is a simplified schematic showing the basic operation of an optical projector.

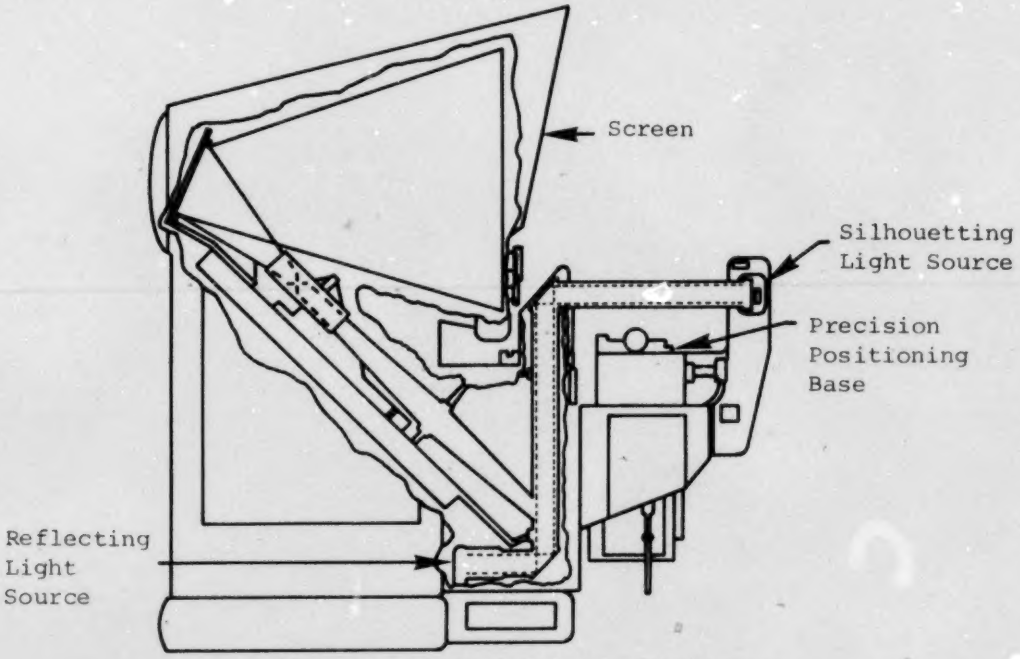


Figure 27-4-13 Optical Projector

For precision measurement, the optical system must project images which are clear, sharp, and dimensionally accurate. The mechanical design and function of the projector must also be compatible with the precision of the optical system. The design must provide ample working space for the positioning of parts. The viewing screen, on which the image is formed, must be located in a position convenient to the operator at normal eye level. Operating controls must be convenient and accessible.

To satisfy these requirements, all optical projectors incorporate in their design several essential features.

- Light Source - High intensity lamps of 1000 watts or more are typically used. Reflecting mirrors project a light beam to collimating lenses. The optical projector in Figure 27-4-13 has two light sources that can be selected. The silhouetting light projects an outline of the part; the reflecting light from the part is projected on the screen.
- Condenser or Collimating Lens System - This system provides for sharp images on the screen by eliminating all but parallel rays of light.
- Workpiece Positioning Table - The part is staged on the table to present the contour or reflecting surface to be viewed on the screen. The optical projector in Figure 27-4-13 has a micrometer lead screw to position the table which provides for precision positioning of the part.
- Mirrors and Lenses - High resolution lenses and highly reflecting mirrors are used to provide a clear, sharp, and magnified image on the screen. The lens and mirror system is designed to give an upright and unreversed image.
- Viewing Screen - Screens are made with fine textured ground glass to provide a glarefree image without localized areas of brilliance. Also, the screen should not introduce distortion of the image or be so bright as to cause eye fatigue.
- Chart-Gages - The effective use of all optical projectors relies upon a chart-gage. It furnishes the point of reference for the operator

when making measurements. Some projectors are furnished with ground glass viewing screens without markings of any kind. They are intended simply as a surface on which an image can be formed. Before any measurements can be made of the image, however, a chart-gage with reference lines must be mounted over the screen. Most projectors, however, are equipped with viewing screens which are also chart-gages. They usually have horizontal and vertical centerlines only, although many also include one or two angular lines as well. Chart-gages of this type provide a positive index of reference lines from which measurements can be taken. Chart-gages are also available in many styles, generally being specially designed for a specific part. Most chart-gages are processed on glass or plastic. They are classified in three types: (1) replacement chart-gages, (2) overscreen chart-gages, and (3) overlay chart-gages.

The first basic use of an optical projector is for so-called toolroom applications and single-piece inspections. Such a projector requires precision in the staging table mechanism and in the measuring devices associated with it. Since measurements are made with reference to a cross line on the center of the projector screen, just as in a toolmaker's microscope, there is no prime requirement for a completely accurate image over the entire screen. A clear, well-defined image will suffice. Movement of the positioning table to place first one boundary of the feature on the cross line and then to place the other boundary on the cross line gives a measurement by the difference in micrometer settings at the two boundaries.

The second basic use of an optical projector is for comparison measurement. In this use, the projected image of the part is compared with an enlarged layout placed directly on the screen. The overlay may be spread over the entire screen area and it must correspond with the magnification setting of the projector. In such applications, accuracy of the image in all areas of the screen is very important. Thus, for toolroom applications prime emphasis is placed on mechanical measuring, while for comparison applications prime emphasis is placed on the accuracy of the optical system.

Since in most industrial plants, projectors are frequently used for both types of inspections, it is generally accepted that equipment must have both a precise optical system and means for precise mechanical measuring.

Principles of Use

There are three basic techniques for measurement generally employed in optical projector usage: (1) measurement by comparison, (2) measurement by movement and (3) measurement by translation.

The inspections performed on many parts are concerned not so much with actual part dimensions as to whether the parts are within permissible tolerance limits. These are essentially go, not-go inspections made by comparison to a master. A chart-gage identifying limits of length, angle, or form serves as the master.

Analytical inspections are concerned generally with the dimensions themselves. It is necessary to make careful measurements of each of the dimensions, and this is usually a slower operation than that which compares a part to a master. Regardless of the type of chart-gage used, precision movement of the part (and/or the protractor for angular measurements) is required for accurate measurement

of specific lengths, angles or form features.

A great many parts contain features that cannot be projected by a light beam directly but whose contours can be measured indirectly by translation. This is accomplished by a combination of tracing and optical projections.

All optical projectors are suitable, within the capability of the optical and mechanical design, for making measurements by comparison. To measure by movement requires a projector with table travel and appropriate measuring devices. Measurement by translation requires special tracer accessories.

The optical projector equipped with optical protractor rings provides the means for making accurate readings of angular values on projectors. The rotational feature also serves as a useful tool in some inspection procedures not directly concerned with angular measurement. Protractors must be as carefully designed and machined as any other part of the projector.

Protractors are standard equipment on most measuring projectors and are available as auxiliary equipment on many others. The rings serve as the holder for the viewing screen. Adjustments are provided in most projectors for exactly centering the screen in the ring although one manufacturer machines rings and glass to avoid this operation. Once assembled, both the protractor ring and the screen should be concentric with the optical axis of the projector.

Degrees of arc are usually marked directly on the rings. Readings are made with correlated verniers having scales readable to one minute of arc. Some of the rings used on very large projectors are marked for every 10° and are used with a continuous-reading dial vernier from which the intermediate degrees and minutes can be read. These vernier dials are readable to one minute of arc also.

To measure angles, the part datum is aligned to a radial datum on the chart-gage such that the vertex is at the center point. Rotation of the chart-gage to align the radial datum with the angle silhouette provides a readout on the protractor.

SURFACE TEXTURE MEASUREMENT

Definitions

The national standard for surface texture is ASA B46.1 sponsored by the American Society of Mechanical Engineers. At the time of this writing, the 1962 revision of B46.1 is undergoing review by a National Standards Committee (B-89). Because possible revisions that may be made are unknown, this section is based on ASA B46.1 - 1962.

Surface texture of many surfaces of parts are important to the function of the part. In particular, mating surfaces are frequently required to perform as bearing or sealing surfaces. The required texture of such surfaces are stipulated on engineering drawings. In this regard, surface texture designations pertain to roughness, waviness and lay.

A number of unique terms are used in the specification of surface texture requirements and the inspection of surfaces for compliance with specified requirements. The student/trainee should memorize the definition of these terms. Figure 27-4-14 illustrates these terms.

- Surface Texture - The repetitive or random deviations from the nominal surface which form the pattern of the surface is called surface texture. Surface texture includes roughness, waviness, lay, and flaws.

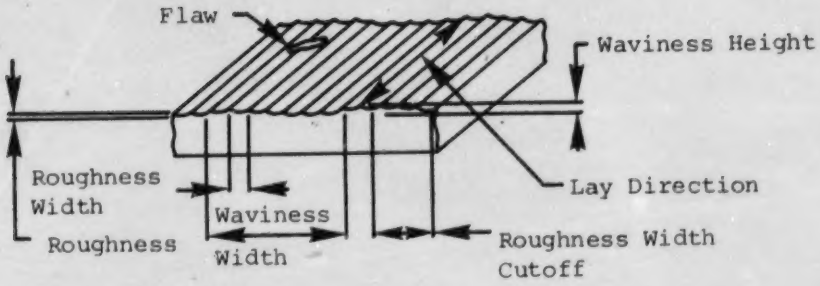


Figure 27-4-14 Surface Texture Terms

- Roughness - Roughness consists of the finer irregularities in the surface texture, usually including those irregularities which result from the inherent action of the production process. These are considered to include traverse feed marks and other irregularities within the limits of the roughness-width cut-off.
- Roughness Height - The arithmetical average deviation expressed in microinches measured normal to the center line is called roughness height.
- Roughness Width - The distance parallel to the nominal surface between successive peaks or ridges which constitute the predominant pattern of the roughness is called roughness width. Roughness width is rated in inches.
- Roughness-Width Cutoff - The greatest spacing of repetitive surface irregularities to be included in the measurement of average roughness height is called the roughness-width cut-off. Roughness-width cutoff is rated in inches. Roughness-width cutoff is always a function of the measuring instrument and it must always be greater than the roughness width in order to

obtain the total roughness height rating. Standard tables list roughness-width cutoff values of 0.003 in., 0.030 in., 0.100 in., 0.300 in. and 1.000 in. When no value is specified, the value of 0.030 in. is assumed.

- Waviness - The widely spaced component of surface texture of generally wider spacing than the roughness-width cutoff is called waviness. Roughness may be considered as superimposed on waviness.
- Waviness Height - The peak-to-valley distance of waviness rated in inches is called waviness height.
- Waviness Width - The spacing of successive wave peaks or successive wave valleys rated in inches is called waviness width. When specified, the values shall be the maximum permissible.
- Lay - The direction of the predominant surface pattern, ordinarily determined by the production method used is called lay.
- Flaws - Irregularities which occur at one place or at relatively infrequent or widely varying intervals in a surface are called flaws. Flaws include such defects as cracks, blow holes, checks, ridges, scratches, etc. Unless otherwise specified, the effect of flaws are not included in the roughness height measurement.
- Profile - The contour of a surface in a plane perpendicular to the surface unless another angle is specified is called profile. Profile is defined to distinguish between surface texture and profile. As described later, some

profiling systems are adaptable to measurement of surface texture.

Symbols

All requirements pertaining to surface texture are contained in the surface texture symbol and its associated data. The symbol, the surface to which it applies and the placement of associated data are illustrated in Figure 27-4-15.

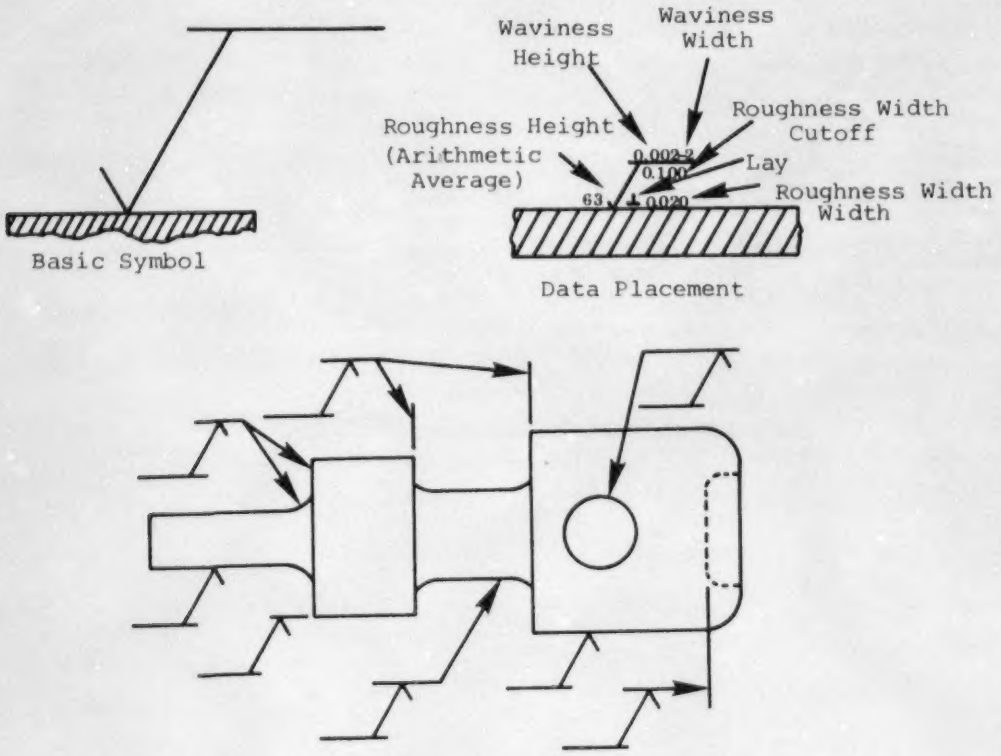


Figure 27-4-15 Surface Texture Symbols

As illustrated in Figure 27-4-15, the basic surface texture symbol is the check mark with a horizontal extension. Figure 27-4-15 also shows the location of values that are shown by drawings for each of the terms applicable to

surface texture. Except for roughness-width cutoff, all values specified by the drawing are maximum values. For the part to be acceptable, measured values must be equal to or less than the maximum specified. In addition to the maximum roughness height, a minimum roughness height may be specified immediately above the maximum value. The value of the roughness width cutoff is used in the measurement procedures. Where a value is not specified by the drawing, 0.030 in. is used.

When specified by the drawing, lay symbols dictate to manufacturing the method of finishing the surface. Inspection of surface texture determines that the finished surface complies with the drawing requirement. Standard lay symbols and their meaning are listed in Table 27-4-2.

Surface Texture Production

Different manufacturing processes commonly result in different surface textures. Table 27-4-3 shows a comparison of roughness height for several manufacturing processes.

SURFACE TEXTURE STYLUS SYSTEM

Description

By far the most common way to measure surface texture is by the movement of a stylus over the surface and the measurement of an electrical signal produced by a transducer attached to the stylus. Such instruments have meter or chart readout or both. While a wide variety of instruments are available with each having its own unique features, all instruments have in common a stylus, transducer, drive mechanism, amplifier and readout. These are illustrated in Figure 27-4-16.

Table 27-4-2 Lay Symbols

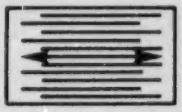
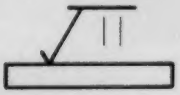
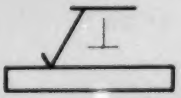
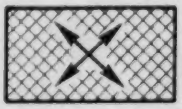
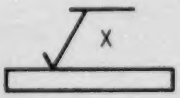
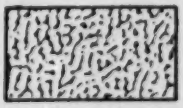
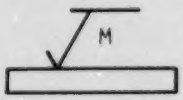
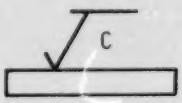
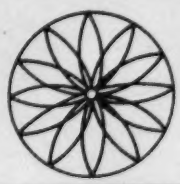
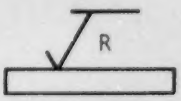
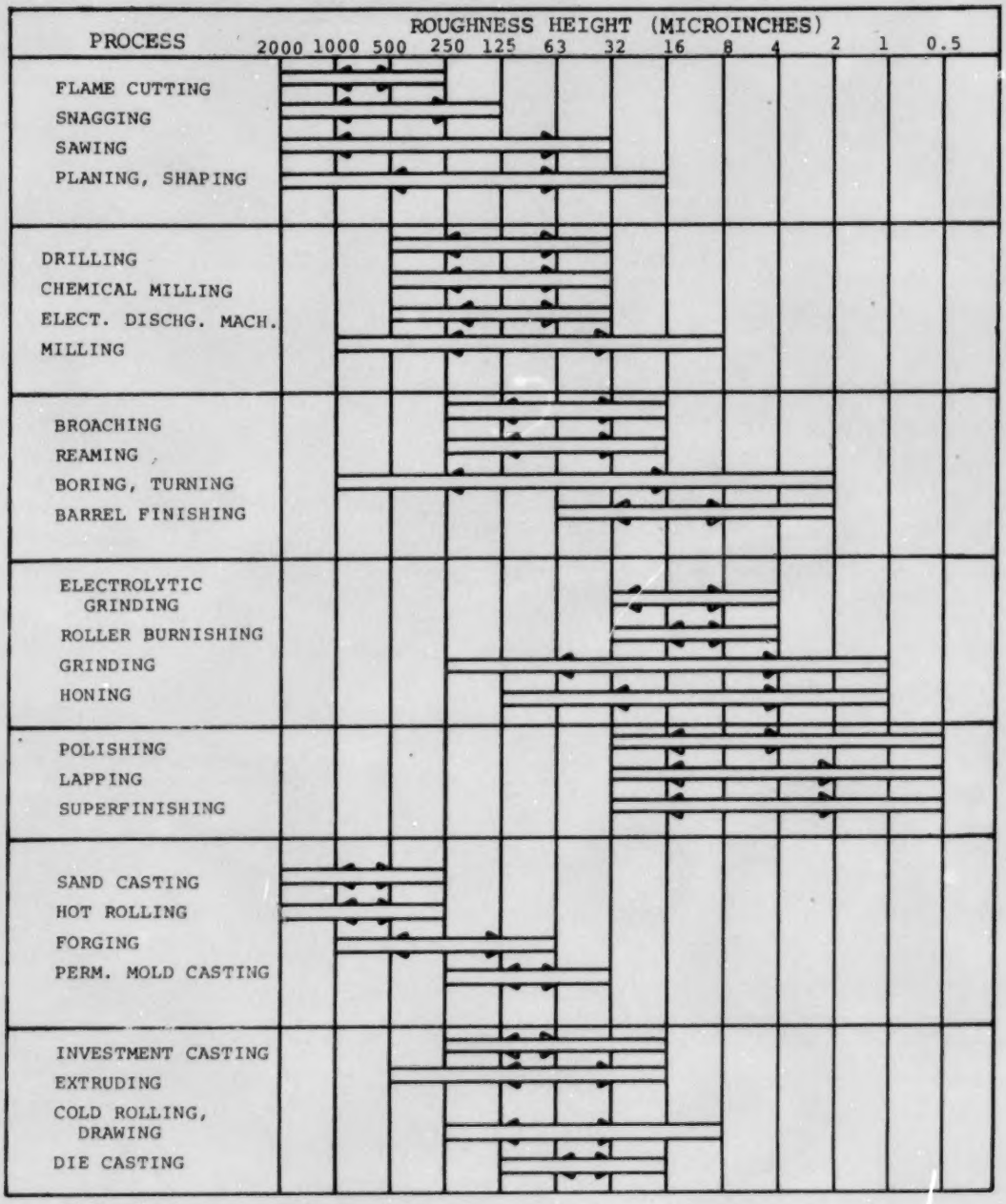
LAY SYMBOL	DESIGNATION	SKETCH OF SURFACE APPEARANCE	APPLICATION
=	Lay parallel to the line representing the surface to which the symbol is applied.		
⊥	Lay perpendicular to the line representing the surface to which the symbol is applied.		
X	Lay angular in both directions to line representing the surface to which symbol is applied.		
M	Lay multidirectional.		
C	Lay approximately circular relative to the center of the surface to which the symbol is applied.		
R	Lay approximately radial relative to the center of the surface to which the symbol is applied.		

Table 27-4-3 Surface Texture Production



The ranges shown are typical of the processes listed. Higher or lower values may be obtained under special conditions.

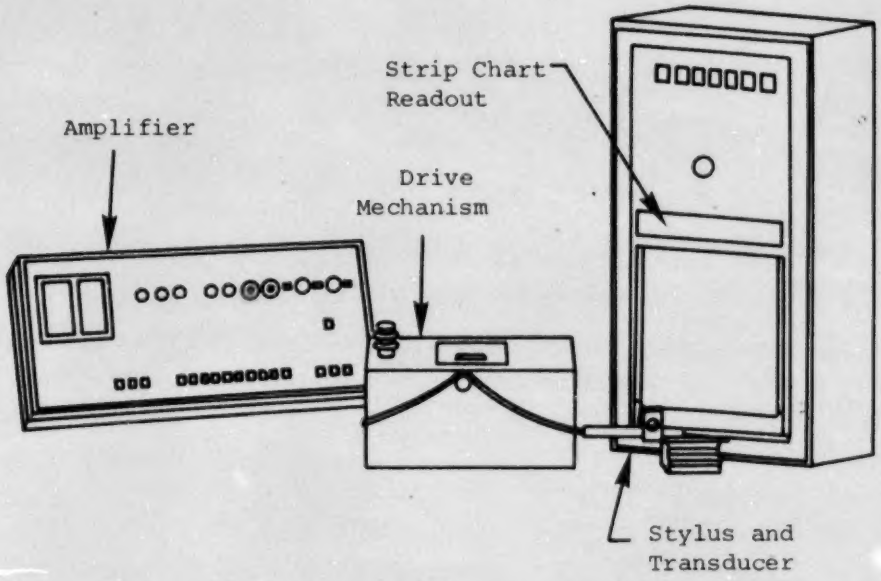


Figure 27-4-16 Surface Texture Stylus System

The stylus is basically a conically shaped needle with a diamond tip. The tip has a spherical vertex with a radius commonly of 0.0001 in. or 0.0005 in. The small radius permits the stylus to follow very small variations in surface texture.

The transducer converts the movement of the stylus into proportional electrical signals. Piezoelectric, electromagnetic and linear variable differential transformer systems are typically used as transducers.

The drive mechanism traverses the stylus over the surface being measured. For accurate results, a uniform speed is essential. Most instruments feature various traversing speeds and stroke length which can be selected. Also, reciprocating traversal is frequently provided. The purpose of a reciprocating traversal is to increase the time of measurement to permit convenient readout on a meter.

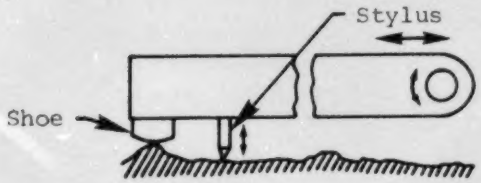
The amplifier contains circuitry not only for amplification of the transducer's output but also for analyzing

the output. Such amplifier analysis provides for meter readout in terms of roughness height. For instruments equipped with recording charts, readout is a trace on a known scale which permits measurement of average roughness, actual roughness, waviness height and width, and total texture (roughness superimposed on waviness).

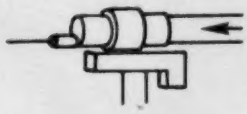
Principles of Use

In the measurement of surface texture, stylus movement in relation to a reference plane provides the basic variable for analysis. The factors affecting the basic variable or the analysis thereof must be known for a meaningful readout. Such factors include the selection of the reference plane, the settings of instrument variables and the inherent features of the instrument.

- Reference Plane - The surface to be measured or an extraneous plane parallel to that surface provides the reference plane. Figure 27-4-16 illustrates two ways to provide the reference surface. The measured surface can provide the reference surface and the basic measurement is the difference in movement between the shoe and stylus. The shoe is selected to have a radius of at least eight times the roughness-width cutoff to prevent entry of the shoe into most



Measured Surface Provides Reference Plane



External Surface Provides Reference Plane

Figure 27-4-17 Reference Planes

irregularities. Straight line skids are also used. Thus, the reference plane is the profile of the surface being measured and the stylus senses variations from the profile. As described later, this type of reference plane is suitable for measuring roughness height but imposes limitations on measuring waviness. An external surface can be used to provide the reference plane. The stylus senses variations from the extraneous reference plane. This type of reference plane is suitable for measuring roughness height and waviness as well as charting actual roughness and profile.

- Direction of Traversal - The direction of traversal is always at right angles to the direction of lay. In this manner, the maximum roughness present is measured.
- Roughness-Width Cutoff - The roughness-width cutoff establishes the distance from which successive stylus data are averaged. It is always wider than the roughness width. If the drawing does not stipulate a value for roughness-width cutoff, it can be determined from Tables in ASA B46.1 if the roughness-width is known. For machining processes, the machine traversal speed equals the roughness-width. For example, machine traversal of 0.015 inch per revolution equals 0.015 inch roughness width. If roughness cannot be determined, a cutoff of 0.030 inch is used.
- Length of Stroke - ASA B46.1 establishes a standard length for measuring roughness height as twenty times the roughness-width cutoff. This assumes that the specific surface examined

is representative of the entire surface. Accordingly, the inspector sets up the equipment to measure what appears to be the area having most roughness. Most instruments continuously average the values from the transducer even when a reciprocating stroke is employed. For such instruments the stroke need not be in one direction only. For example, for an 0.030 in. cutoff, the 0.6 in. stroke (20 x 0.030 in.) could be two cycles of a 0.150 in. reciprocating stroke.

- Roughness Averaging - The roughness averaging system typically consists of an AC amplifier, attenuators, averaging circuits, and a meter that reads roughness height in microinches. Output jacks permit hook-up to a chart recorder. Such an averaging system eliminates waviness from the data being averaged by the combination of traversal speed of the pickup head and the roughness-width cutoff. This is accomplished electronically by attenuating frequencies below a value expressed by Equation 27-4-4:

$$\text{Low Frequency Cutoff} = \frac{\text{Traversal Speed (in./sec)}}{\text{Roughness-Width Cutoff (in.)}} \quad \text{(Eq. 27-4-4)}$$

The relationship of the amplifier and drive unit settings must therefore, be known for each type of instrument used. Such relationship is described by literature provided by the equipment supplier (e.g., roughness-width cutoff settings are valid at 0.3 in./sec traversal speed.) The roughness-width cutoff identifies the maximum spacing of surface irregularities

that are passed by the amplifier to the readout. For example, when an instrument's roughness-width cutoff setting of 0.030 is valid at a 0.3 in./sec traversal speed, it is known that irregularities spaced wider than 0.030 in. are blocked. Therefore, if a strip chart were connected to the amplifier's output, irregularities wider than 0.030 in. would not be recorded. Wider intervals can be recorded if traversal speed is slowed. For example, if the above traversal speed is slowed to 0.1 in./sec, the effective roughness-width cutoff is essentially three times the switch setting of 0.030 in. Shifting from an AC amplifier to a DC amplifier reduces the roughness width cutoff to zero and provides a theoretical infinite spacing that can be charted. However, if skids or shoes are used for the reference plane, a mechanical limit is imposed due to the skid following the wider irregularities. The mechanical limit is the radius of shoes divided by eight or for straight line skids, the length of stroke. The logical conclusion is that averaging systems are basically designed to measure roughness height and any other use requires careful analysis of the manufacturer's literature to determine the limitations associated with recording waviness or profile.

- Profiling - Profiling systems use a DC amplifier and a chart recorder that plots surface features on a calibrated scale. The system is basically designed to plot profile and essentially has a zero roughness-width cutoff or infinite spacing of irregularities that are recorded. However,

use of skids or shoes for establishing the reference plane will introduce mechanical limits on the maximum spacing as previously described. The combination of recorder frequency response and traversal speed sets the limit on the narrowest spacing that will be recorded as expressed by the Equation 27-4-5:

$$\text{Narrowest Spacing (in.)} = \frac{\text{Traversal Speed (in./sec)}}{\text{Recorder Frequency Response (Hertz)}} \quad \text{(Eq. 27-4-5)}$$

For example, a traversal speed of 0.1 in./sec and a 100 Hertz frequency response gives the limit of 0.001 in. as the narrowest spacing that can be recorded. A much narrower spacing can be recorded if the traversal speed can be slowed considerably. Otherwise, difficulty exists in recording roughness of surfaces that are finished with finely spaced irregularities. Again, instrument capabilities must be known to determine the limitations of using profiling systems to plot roughness height.

Accuracy and Error Sources

Accuracy of roughness height and waviness measurements is primarily dependent on the equipment capabilities. Therefore, calibration methods are used to determine accuracy. For calibration of roughness height measurements, standard blocks having areas of precisely known roughness are traced and compared with indicated values. For example, the instrument may be adjusted to exactly match the 125 microinch roughness height area of a calibration block. Then other roughness areas of the standard are traced and the readout is plotted to establish a cali-

bration curve. The deviation between the readout and the known roughness of the standard provides the error by which measurement of product are corrected.

For calibration of waviness measurements, standard blocks having known small step changes in contour are traced. The readout is compared with the known values to determine error. Gage blocks can also be arranged to provide a stepped calibration block.

Applications

Surface texture measurements are specified by engineering drawings when the surface roughness plays an important role in the function of that surface.

- Resistance to Wear - Roughness of load bearing surfaces tends to expose peaks to the load and results in increased wear. Also, deformation can result due to localization of stresses at points of excess roughness. This becomes very important on the leading flank of gears.
- Supportive of Lubricating Film - Excessive roughness provides peaks above the level of lubricating film causing metal-to-metal contact which should have been eliminated by the film. Conversely, some roughness is necessary to drag the lubricant between moving members.
- Clearance of Mating Parts - Roughness of the part or the sensor of the measuring device causes the dimensional inspection results to portray a larger material condition than actually exists. Therefore, close fit conditions are not actually met. Such effect on gage block stacks would be staggering were it not for the fine surface texture required of gage blocks.

- Resistance to Corrosion - Roughness tends to trap corrosive materials and serve as cells of incipient corrosion.
- Low Coefficient of Friction - Roughness plays a crucial role in the friction of ball and roller bearings and sliding surfaces.
- Esthetic Value - Many products have low roughness for sake of appearance. Automobile bodies are an example. In nuclear power plants, another driving factor is the ability to decontaminate the surface should radioactive material come into contact with that surface. Therefore, working surfaces in a radiation laboratory frequently use sheet metals having low roughness height.

EXERCISES

The following exercises reinforce the information presented in this module.

1. Given assignments to students/trainees to make angular measurements with a universal bevel protractor. Any parts with angles which are accessible by the bevel protractor may be used. Each assignment should require the student/trainee to demonstrate proficiency in (1) manipulative skills, including comfortable handling of the device, accurate placement of straight edges against angle boundaries, and adjustment of thumb lock nut without affecting the measurement, and (2) readout skills, including ability to differentiate between direct angles and supplements, and accurate reading of vernier.
2. Give assignments to students/trainees to make angular measurements with sine bars. Parts selected for measurement should contain angular features which are toleranced to one degree or less. Table 27-4-4 is a data table for use with each assignment.
3. Give assignments to students/trainees to make linear and angular measurements with engineering microscopes. Prior to such assignments, instruction should be given on the operation of the particular engineering microscope available for use. Each assignment should develop the skills of (1) establishment of datum, including part mounting for either silhouetting or reflecting image and perpendicularity of feature plane with optical system, (2) indexing of part, with and without supplementary gage blocks, and (3) accurate readout, including scale interpretation and accurate calculations.
4. Give assignments to students/trainees to make linear, angular and/or thread form measurements with optical

projectors. Prior to such assignments, instruction should be given on the operation of the particular optical projector to be used. Each assignment should require demonstration of (1) establishment of datum, including part mounting and parallelism of feature plane to optical system, (2) selection of chart-gage to match part feature to be measured, (3) manipulation, including staging of chart-gage, and (4) accurate readout.

5. Give assignments to students/trainees to measure surface texture in terms of roughness height and waviness. Prior to such assignments, instruction should be given on the specific surface texture measuring equipment to be used. Each assignment should require demonstration of (1) calculation of roughness-width cutoff, (2) establishment of reference plane, (3) set-up, including stroke length, traversal speed and equipment settings, and (4) readout, including meter for roughness height and chart for waviness.

MATERIALS

The following materials are required to support this module:

1. Universal Bevel Protractor
2. Sine Bar
3. Gage Block Set
4. Height Indicator Gage (Mechanical or Electronic)
5. Universal Measuring Microscope or Similar Instrument Employing an Engineering Microscope

6. Optical Projector
7. Gage-Charts for Optical Projector (Specific types of match part features to be measured)
8. Stylus Trace Type of Surface Texture Measuring Equipment (Averaging or Profiling Equipment or Both)
9. Parts for Measurement, Features should include Acute and Obtuse Angles, Screw Threads, Inside and Outside Dimensions, Geometric Forms of Parallelism and Perpendicularity)

PROCEDURES

The suggested exercises involve a series of measurements using the following equipment. The following procedure is intended to assist the instructor/student in performing these exercises. It is also suggested that the student/trainee make reference to the discussion given in this module for further details.

Universal Bevel Protractor

1. The universal bevel protractor provides for the direct measurement of angles or their supplements by placement of precision straight edges on the boundaries of the angle.
2. Readout begins at the vernier zero and concludes with the vernier line which is coincident to a primary scale line in the same direction as from zero of the primary scale.

3. In actual measurements, one must be observant of whether the readout is the measured angle or its supplement.
4. Perform an angular measurement of an acute, obtuse and a straight angle reading the angular measure to the nearest 5 minutes.
5. Instrument error sources include straightness of the blade edges, bearing accuracy of the rotatable blade, and scale accuracy.
6. Procedural error sources include manipulative errors, readout errors, and unclear bearing surfaces.

Sine Bar

1. The sine bar (or block or plate) provides a constant hypotenuse of known length which can be used with gage blocks and height indicators for the measurement of angles.
2. Given the value of the angle by the part drawing, the gage block height needed for the measurement can be calculated by the formula $h = c \sin \theta$.
3. In determining gage block height, attention must be given to the method of mounting the part on the sine bar because the method of mounting can affect the relationship of the sine bar plane to the part feature.
4. Measurement of height deviation permits calculation of angular deviation by the formula $\tan \phi = \frac{i}{\ell}$.
5. Using the sine bar and gage blocks, measure the angle of a metal block cut at an angle similar to the example shown on page 27-4-15 of this module. Measure the angle to the nearest 10 seconds of arc.
6. Repeat step 5 for a second block.

7. Error sources of the sine bar are flatness and squareness of working surface, roundness and straightness of cylinders, parallelism of cylinders with each other and the working surface, and accuracy of the center distance between cylinders.
8. Error sources of measurements with sine bars include misalignment in the mounting of parts, precision of measuring the length over which the height variation is explored, errors of the height gage, flatness of the surface plate, and calculation errors.
9. Sine bars are preferred over universal bevel protractors when angles are inaccessible to the bevel protractor or when angles are toleranced in minutes.

Engineering Microscope

1. Engineering microscopes are optically assisted instruments for measuring lengths, angles, and forms.
2. The optical system permits accurate silhouetting or reflecting a part feature against a graduated scale.
3. Measurements are taken from micrometer lead screws, graduated scales within the optics system, or the combination of these two.
4. Angular measurements are provided by a protractor within the graticle chamber.
5. Measure the length of a gage block to the nearest 0.001 inch.
6. Using the engineering microscope, measure the angle of an angular block as previously done with a sine bar, but read the answer to the nearest minute of arc.

Optical Projector

1. Optical projectors are optically assisted instruments which project the part image on a screen for the measurement of lengths, angles and forms.
2. A silhouetting or reflecting image may be projected dependent on the design of the specific optical projector.
3. Basic components of any optical projector include light source, collimating lens system, workpiece positioning table, mirrors and lenses, viewing screen, and chart gages.
4. The two basic uses of optical projectors is for linear measurements and comparative measurements.
5. The three basic measurement techniques are comparison, movement, and translation.
6. Angular measurements are made by use of protractor rings to which the chart gage is mounted.
7. Using the optical projector, measure the angle of an angular block. Measure the angle to the nearest 30 minutes.
8. Measure the dimensions of a not go gage using an optical projector.

Surface Texture Measurement

1. Surface texture refers to roughness, waviness and lay.
2. Roughness is the finer irregularities in surface texture and is measured in roughness height expressed as the arithmetical average deviation from the center line in microinches.
3. Roughness-width cutoff establishes the greatest spacing of irregularities to be included in the roughness height measurement.

4. Waviness is the widely spaced component of surface texture and is generally wider than the roughness width cutoff. Its height is expressed as the peak to valley distance in inches.

5. Lay is the direction of the predominant surface pattern and is specified on drawings by the following symbols:

SYMBOL	DESIGNATION
∥	Parallel
⊥	Perpendicular
X	Angular in Two Directions
M	Multidirections
C	Circular
R	Radial

6. Using a surface texture stylus system, similar to that described in Figure 27-4-15, make measurements of:
   a. Roughness height
   b. Roughness width
   c. Roughness width
   d. Roughness height

DATA TABLE

Table 27-4-4 Sine Bar Data Table

Equipment Serial Number

Sine Bar _____ Height Gage _____

Surface Plate _____ Test Indicator _____

Part Description

Name _____ Serial Number _____

Feature (Sketch the feature and label with tolerance.)

Calculations

Gage Block Height ($h = c \sin \theta$):

Variation of angle being measured ($\tan \phi = \frac{i}{\ell}$)

Value of angle measured:

REFERENCE MATERIALS

ASA B46.1-1962, Surface Texture, The American Society of Mechanical Engineers, New York New York

Busch, Ted, Fundamentals of Dimensional Measurement, Delmar Publishers

Farago, Francis T., Handbook of Dimensional Measurement, Industrial Press, Inc.

Handbook of Industrial Metrology, Society of Manufacturing Engineers, Prentice-Hall, Inc.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answer brief. Use the backs of the test if you need more space.

1. Describe how angles are measured with the universal bevel protractor.

_____

_____

_____

_____

2. Name three sources of error in measurements with the universal bevel protractor.

a. _____

_____

b. _____

_____

c. _____

_____

3. Give the reading the universal bevel protractor scales illustrated below:

Needs a. Reading _____ also

b. Reading _____.

4. Describe how angles are measured with a sine bar.

5. Name three error sources associated with measurements with the sine bar.

a. _____

b. _____

c. _____

6. Describe how angles are measured with the engineering microscope.

7. Name three error sources associated with measurements with the engineering microscope.

a. _____

_____

b. _____

_____

c. _____

_____

8. Describe how angles are measured with the optical projector.

_____

_____

_____

_____

_____

_____

_____

_____

9. Name three error sources associated with measurements with optical projectors.

a. _____

_____

b. _____

_____

c. _____

_____

10. Describe how an optical projector is used to measure form such as thread form.

_____

_____

11. Define the following terms related to surface texture:

a. Roughness

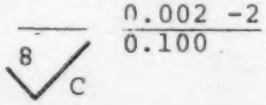
b. Roughness height

c. Roughness-width cutoff

d. Waviness

e. Lay

12. What is the meaning of the following symbol?



a. Basic symbol is:
b. 8 means:
c. 0.002 means:
d. 2 means:
e. 0.100 means:
f. C means:

13. Describe how the inspector determines the direction of traversal of the stylus used for surface texture measurement. Why is this direction used?

14. Describe why roughness height measuring equipment which uses the profile of the measured surface as the reference plane imposes limitation on measuring waviness with the same equipment.

15. Describe the use of standard roughness blocks with respect to roughness measuring equipment.